3TEX

Engineered Fiber Products

3D Woven Carbon-Glass Hybrid Wind Turbine Blades

Wind Turbine Blade Workshop
Albuquerque, New Mexico
February 24-25, 2004

Mansour Mohamed

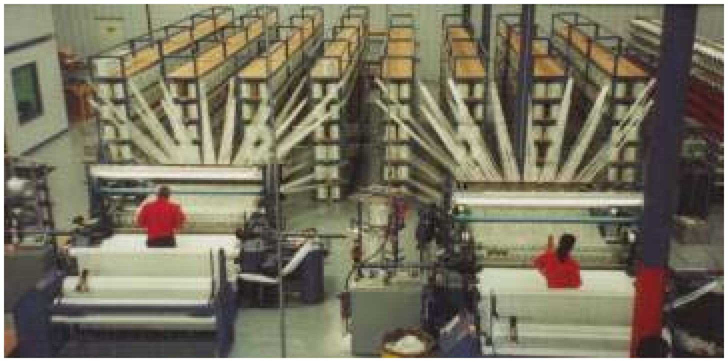
www.3tex.com

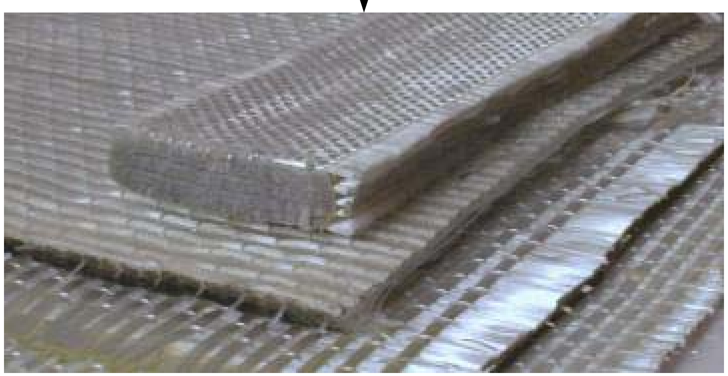
National Wind Technology Center

3TEX Role in Composite Mfg.

3TEX

Preforms + Reinforcements
+ Eng. Services





- Utilities/Infrastructure
- Transportation
- Sports/Recreation
- Marine
- Defense

End Markets

Composites Fabrication

COMPANY INFORMATION

Cary, North Carolina (30,000 sq. ft.)

Rutherfordton, North Carolina
(Plant 1 30,000 sq. ft.)

- **Commercializing 3D Weaving Technology Invented at NC State University**
- **Award Winning 3WEAVE™ Technology Recognized**
- **Cost and performance advantages in end structure**
- **20 Standard, 130 Specialty/Custom Products**
- **Provide custom engineering and development for integrated product design**
- **Converting into commercialization phase with Product Evaluations at 20+ Companies**
- **12 Patents licensed, issued or pending**
- **Market channels and distribution in place**
- **22 Employees in 2 locations**
- **80,000+ square feet of manufacturing space**

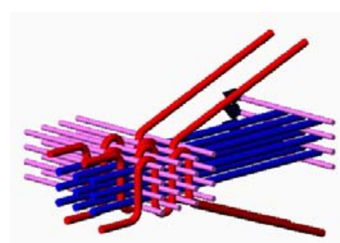
•Ready supply of standard products with technical/sales support

•Ready to custom engineer products for partners and customers

3TEX 3WEAVE™ 3D Weaving

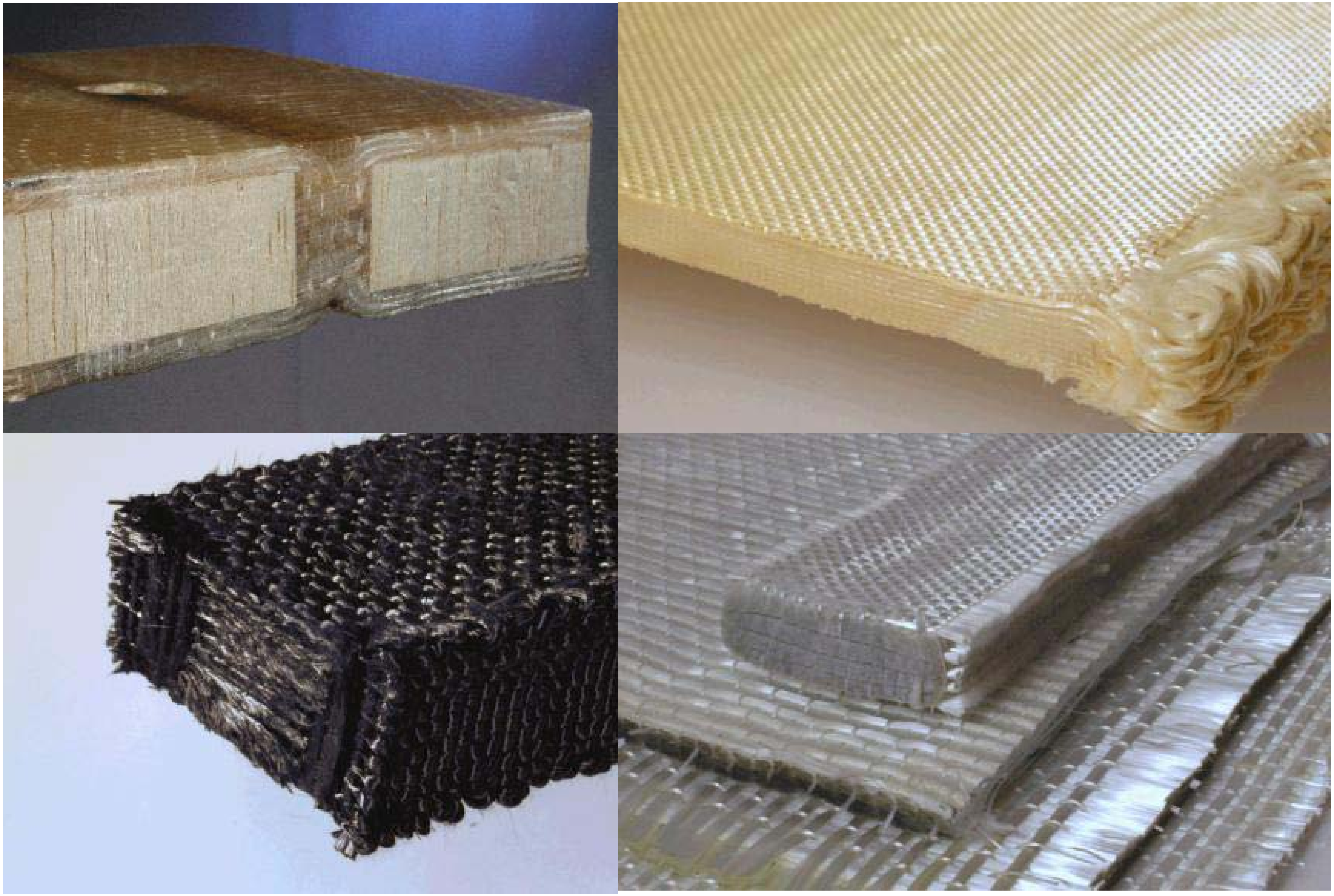
Relative to Standard 2D

- **Improves material performance**
  - Non-crimp straight fibers = higher strength and stiffness
  - Z direction fiber = improved fracture toughness and damage tolerance
- **Lowers fabricated component cost**
  - Faster resin wet-out = shorter processing times
  - Thicker/net-shape and higher conformability = labor savings
  - Better properties = use less material
- **Improves quality**
  - Thicker and/or net-shape = fewer pieces less assembly error
  - Automated textile processing = consistent quality



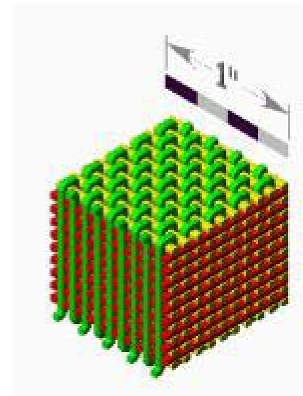
3WEAVE™ Process

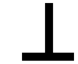
Examples of Forms made by Integral 3D Weaving



Existing 3WEAVE™ Capabilities


- **Width** (y) - 2 in. to **72 in**.
- Thickness (z) - < 0.1 in. to 1.0 in.
- Length (x) - continuous, cut lengths <1ft to >20ft



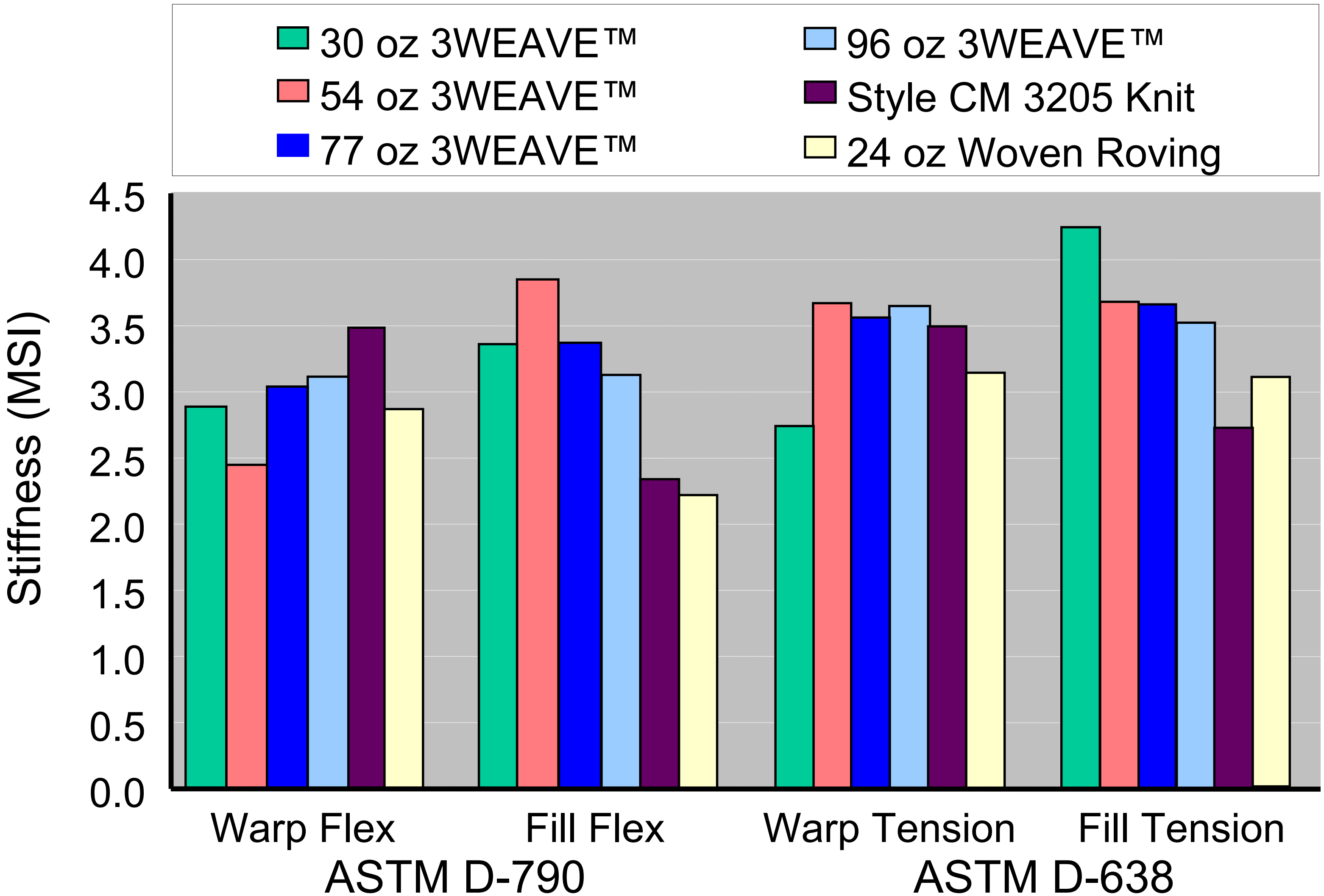


- **Shapes** - Billets, plates, sheets, T, I, Π, cruciform's, angles, pockets, tubes, boxes, etc.

- Carbon Fiber - 1k to 320k - PAN or Pitch
  70 Msi stiffest to date
- Small Glass Yarns to large Glass rovings
- Unit Cell dimensions - 0.020 in. to 0.200 in.
- **Controlled Fiber Distribution**
  - XYZ, 3D Orthogonal Weave, 0/90/Z
  - Fiber Vol. Fractions > 55% as woven
  - Tow packing factors > 65%
  - Uni-directional to XYZ balanced
  - Straight internal tow – non-crimp

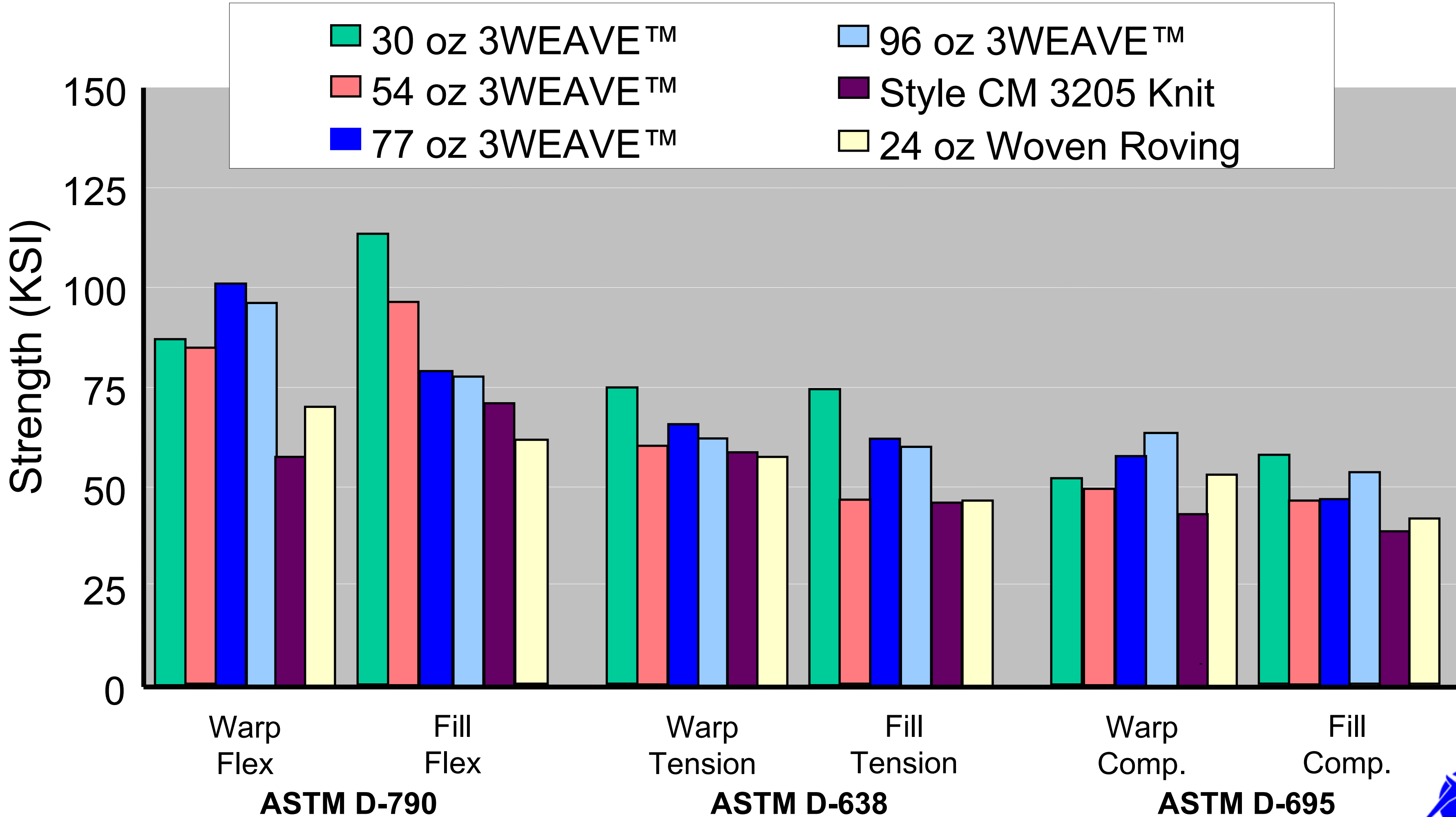
Stiffness Comparison

E-Glass/Vinyl Ester vacuum-infused panels (65 – 70% by weight)
Tests performed at PPG Reinforcements Technical Center



Strength Comparison

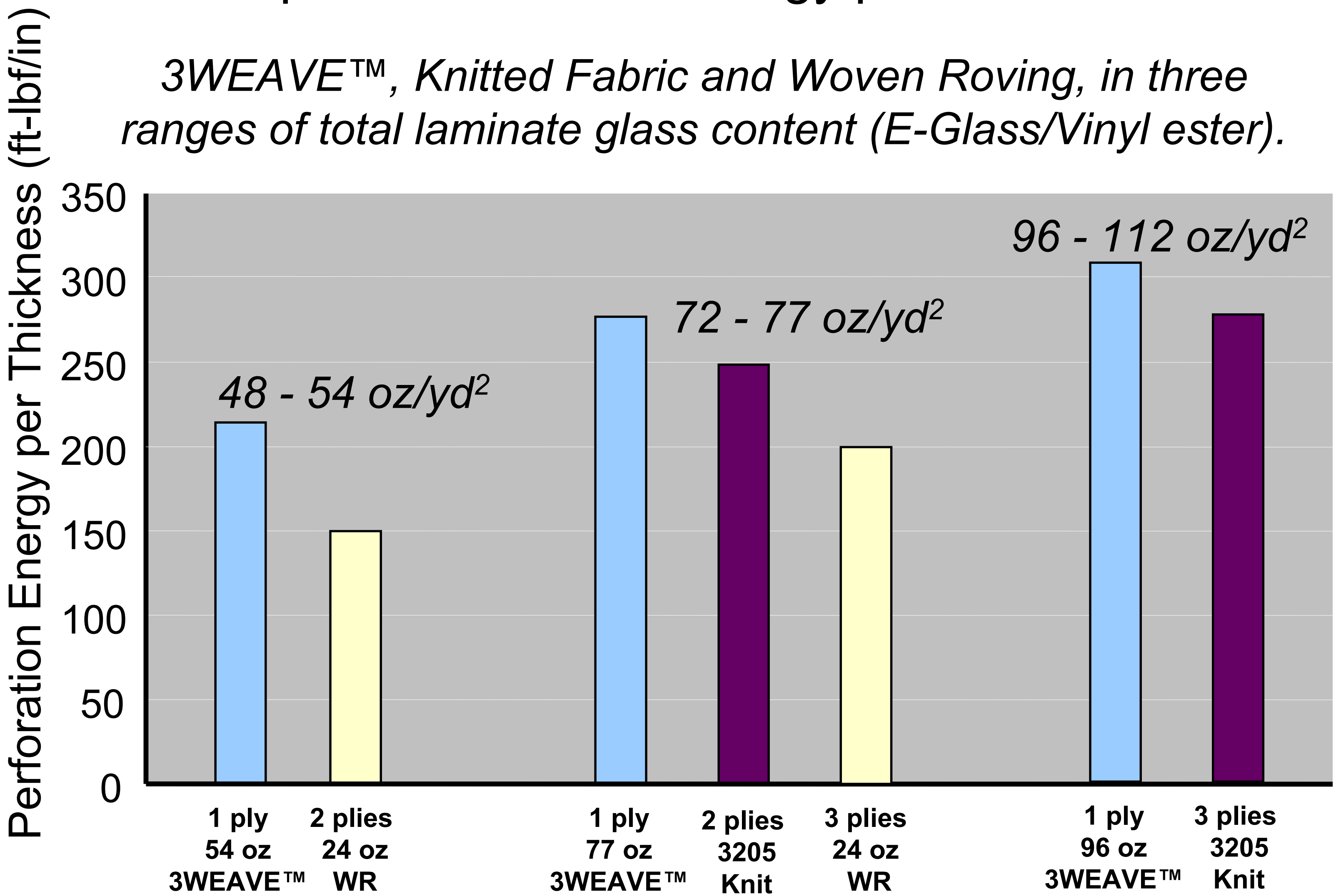
E-Glass/Vinyl Ester vacuum-infused panels (65 – 70% by weight)
Tests performed at PPG Reinforcements Technical Center



Impact Damage Tolerance

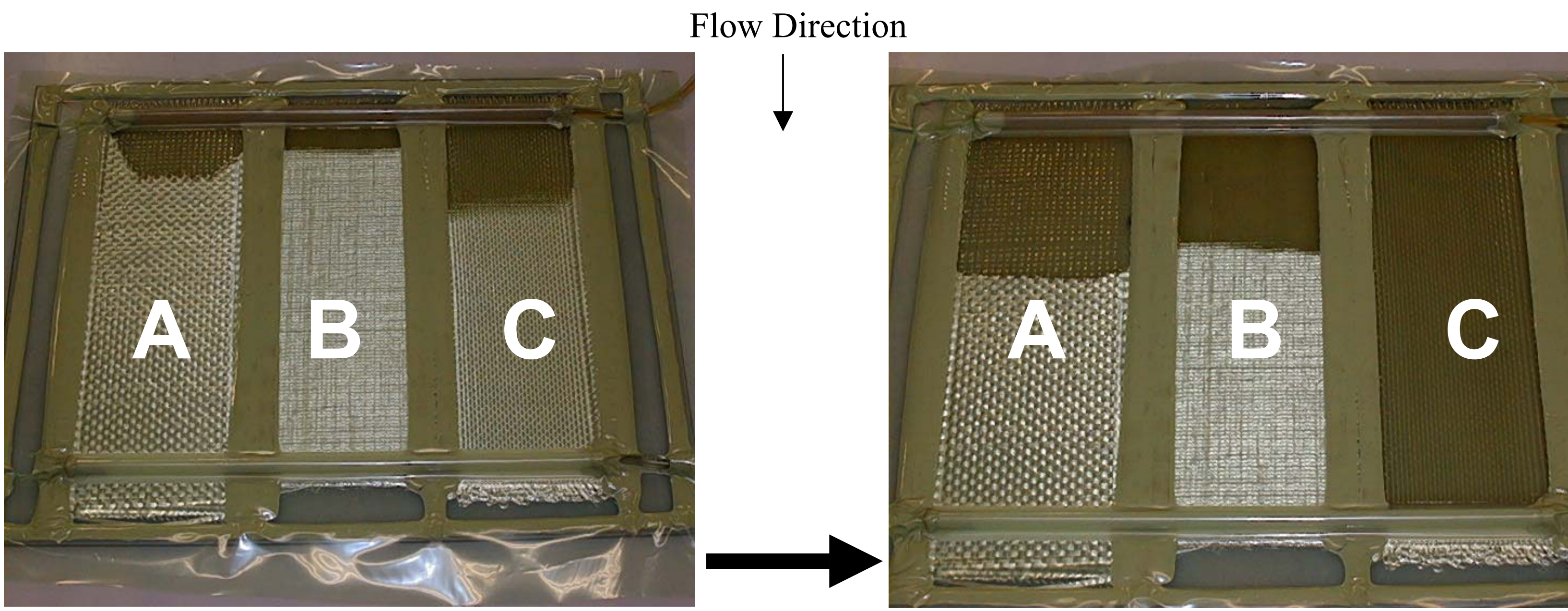
Impact Perforation Energy per Thickness

3WEAVE™, Knitted Fabric and Woven Roving, in three ranges of total laminate glass content (E-Glass/Vinyl ester).



Resin Wet-out Speed and Permeability

Vacuum infusion - all samples ~ 96 oz/yd^2 glass roving content
Vinyl ester resin from common source to common outlet



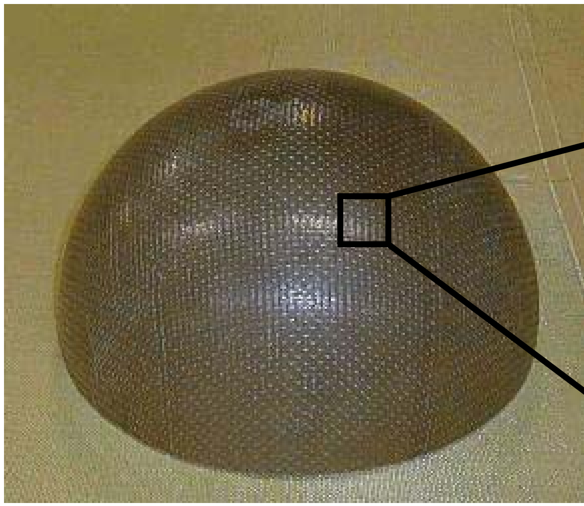
A: 4 plies 24 oz/yd^2 Woven Roving

B: 3 plies Style 3205 Knitted Fabric

C: 1 ply 96 oz/yd^2 3WEAVE™

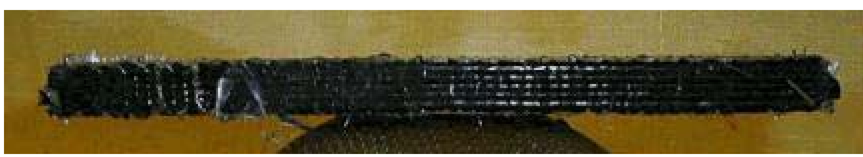
National Wind Technology Center

Formability of 3WEAVE™



77 oz E-Glass 3WEAVE™ molded into hemisphere without wrinkling or buckling

Carbon-Glass Hybrid, XY Balanced Preform, 0.7” Thick
Conforms to compound curvature



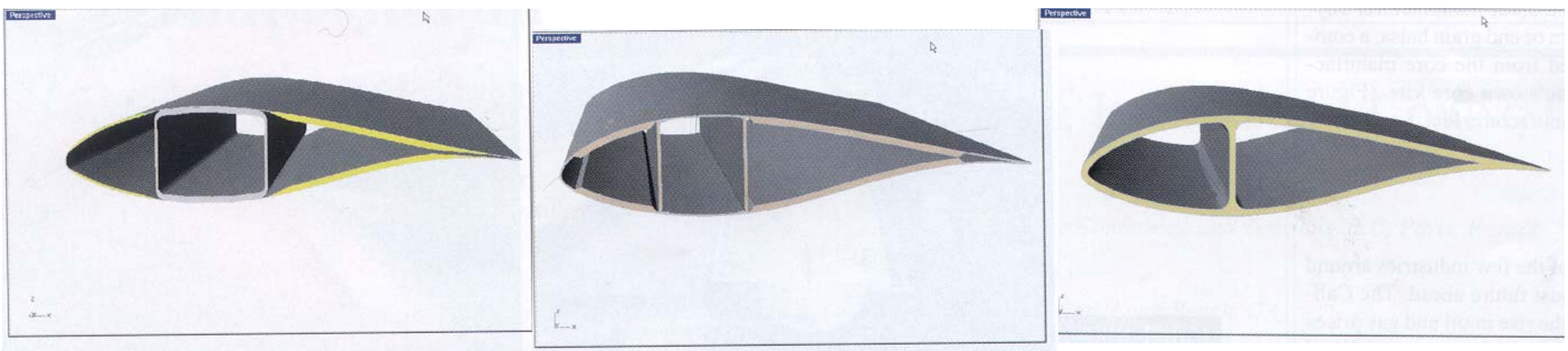
3D Woven Carbon-Glass Hybrid Wind Turbine Blades

- DOE Phase I SBIR - $100,000 - 7/22/02 to 4/21/03
- DOE Phase II SBIR - $666,375 - 6/27/03 to 6/26/05
- Topic 18a "Carbon Fiber Composites for Wind Turbine Blades"
- Principal Investigator – Mansour Mohamed
- Project Officer – Jack Cadogan, DOE in DC
- Use carbon fiber to enable bigger blades (>50m)

Sandia National Laboratories

Background

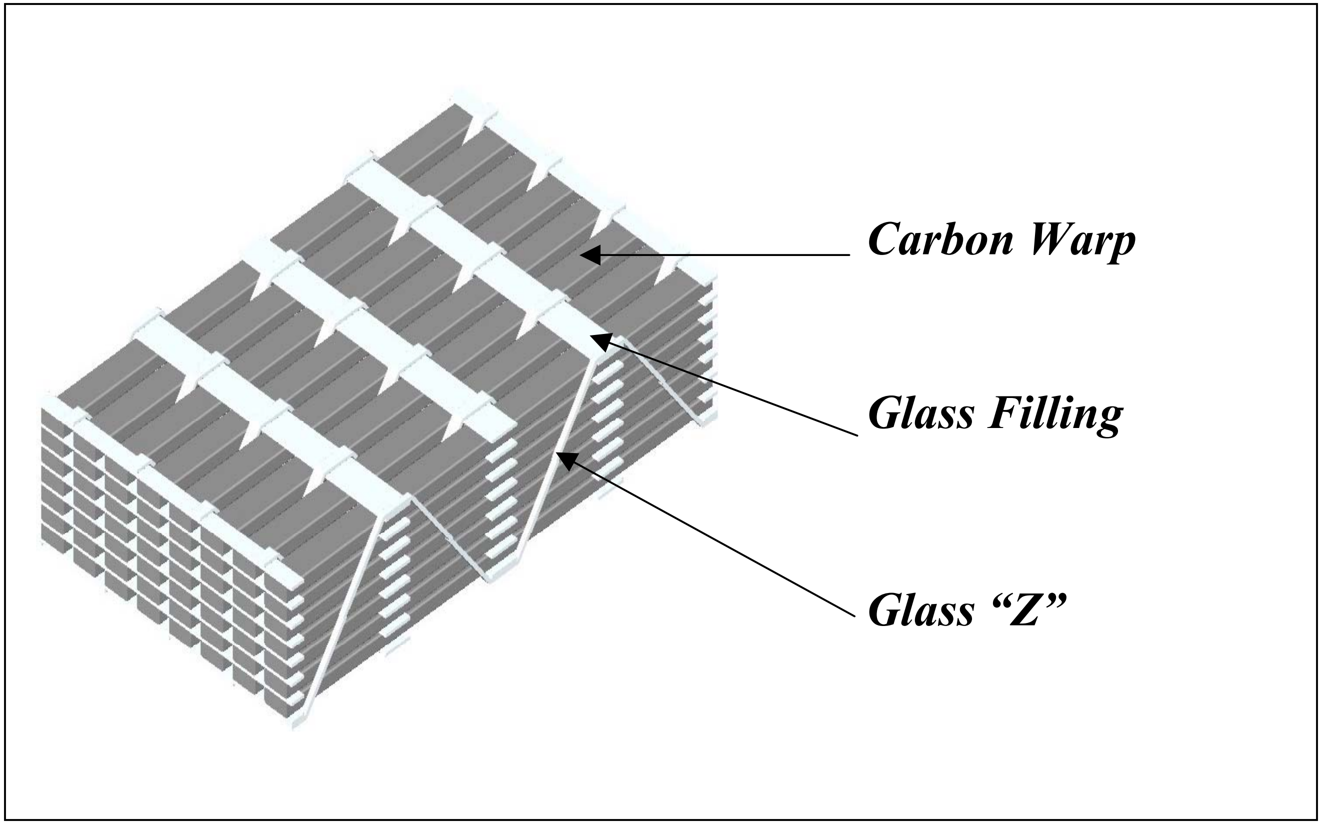
- Most current blades – Spar type design
- Bigger blades – more stiffness driven
- Carbon stiffer but more expensive than glass
- Ideas
  - Hybrid Glass/Carbon – Carbon only where most effective
  - Faster/cheaper manufacturing – e.g. less wet lay-up more VIP
  - Innovative design approaches – new spar cap design; optimized sandwich; etc.



3TEX Approach

- **Use 3WEAVE™ materials with resin infusion**
- **Hybridized carbon/glass 3WEAVE™**
- **Baltek variable density balsa core for optimized sandwich design**
- **"Integrated research team"**
  - **3TEX (Program lead, preform design and 3D weaving)**
  - Baltek (balsa core, sandwich testing)
  - Wetzel Engineering, Inc. – (Blade design and analysis)
  - Molded Fiberglass Companies, MFG/West – (Infusion, testing, and Subarticle and Prototype Blade Manufacture)
  - GE Wind Energy Systems, (Baseline design Information, and tooling)
  - Toray Carbon Fibers America (fiber and technical input)
  - PPG Industries (fiber, technical input, and laminate testing)
  - Ashland Chemical (Modar resin, panel fabrication, laminate testing)
  - NREL (testing of Subarticle, and Prototype Blade)

Carbon /Glass Hybrid
100% Carbon Warp with Glass Filling and Z



New Spar Cap Design Concept

- Constant thickness Variable Width 3WEAVE™ Material
- Weave one panel to be cut into two tapered panels
  for the upper and lower spar caps
- Minimum waste leads to lower cost
- Use variable density balsa in the spar cap to provide required thickness

Optimized Sandwich Concept

- View among blade designers is that core is just a spacer.
- All core materials are not the same
  - Balsa has twice shear strength than foam
  - Four times the shear modulus than foam
  - High compressive and tensile strengths for better buckling resistance
  - Better fatigue strength
- Reducing density of balsa does not greatly deteriorate structural performance of laminate
- Reducing density of foam greatly affects properties of laminate
  - Core thickness must be increased to compensate
- Variable density balsa core puts properties where they are needed
  - Greater strength at the blade root - Less weight at the tip

Phase I Conclusions

- Single piece of 3WEAVE fabric with constant thickness and variable width, simplifies the manufacturing process by eliminating the need for lamination of a large number of layers and the dropping of plies to reduce the stiffness toward the tip of the blade, which could be sites for stress concentrations.

- Hybrid design selected avoids mixing glass and carbon in the same direction, thus reducing the thickness of the Spar Cap and in turn the blade weight. The preferred design has 100% carbon warp with 100% glass filling and Z.

- For a 37-m blade designed for IEC Class IIA conditions, a spar cap root width between 750 and 1,000 mm is most cost effective over the entire range of composite stiffness values examined (5 to 16.4 Msi).

Phase I Conclusions

- A Spar Cap material stiffness of 16 Msi, which was exceeded in Phase I, results in weight reduction of between 30 and 33% compared to the baseline hand lay-up blade.

- Using 3WEAVE E-glass material for all or part of the skins could result in substantial (10-20%) reductions in blade mass, relative to the already lighter 3WEAVE baseline blade. Variable density balsa combined with the new blade design might result in substantial weight and cost savings.

Phase II Objectives

Overall - demonstrate feasibility of hybrid carbon/glass 3WEAVE™/balsa sandwich for large blades

- Perform comprehensive analytical studies of the selected materials and blade component designs using ANSYS commercial finite element code and 3TEX in-house 3D MOSAIC structural analysis code and use results for the optimal blade design.
- Finalize material optimization for the selected wind turbine blade based on the results of the Phase I project and new analytical and experimental results.
- Manufacture spar box subarticle utilizing 3WEAVE™ hybrid glass material.

Phase II Objectives

- Test the subarticle and at the DOE National Renewable Energy Laboratory (NREL).
- Manufacture a prototype 24m blade using the optimized designs and resin infusion process.
- Perform and document a comprehensive cost analysis of the blade manufacturing approach, to determine cost advantages provided by the new concept and 3WEAVE™ materials.
- Test the prototype blade at NREL
- Prepare final technical report and results for publication.
- Develop commercialization plans.

Results of the New Concept

Blade	3WEAVE Thickness	Spar Cap Root mm	Width Tip mm	Tip Deflection mm	Maximum Tensile Strain	Spar Cap Weight kg	Blade Weight kg	Change in Blade Mass	Root Static Moment kg m
Z50 Baseline (36% FVF)	n/a	952	635	1736	4054	1085.8	2628.1		20859
Z50 VARTM Glass (55% fvf)	n/a	952	635	1736	4054	835.6	2175.3	-17.2%	17113
0653-525-103	6.53	525	103	1733	3694	114.6	1467	-44.2%	10552

Note: The baseline Z50 blade is fabricated using wet hand layup with an estimated fiber volume fraction of 36%

The VARTM Glass blade is for analysis purposes only and maintains the same laminate structure with a fiber volume fraction of 55%

Status

- Identified 3WEAVE™ material design and properties using Toray T 700 carbon, PPG Hybon 2022 E-glass, and Modar 865, urethane modified acrylic by Ashland Chemical as the resin
- GE provided all information needed for the design of their 24 m blade
- Initial designs of the subarticle and prototype blade by Kyle Wetzel started
- Plans to manufacture of the spar subarticle at MFG are underway
- GE Z50 mold will be used to manufacture the 24m prototype blade at MFG
- Discussions with Walt Musial related to the testing plans are underway

Acknowledgements

- Funding from DOE for the Phase II activities and the guidance provided by the program officer Jack Cadogan are very much appreciated

- The cost sharing and technical assistance provided by GE, MFG Companies, Ashland Chemical, Baltek Corporation, PPG, and Toray are critical to the success of this project

- The technical assistance provided by Kyle Wetzel and Walt Musial is invaluable to the program